ELECTRICAL BREAKDOWN IN SPARK COUNTER

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ABSTRACT. Spark counter voltage pulses due to sparks produced by Po^{210} α-particles in atmospheric air were photographed on a Tektronix 531-A Oscilloscope using a fast quenching circuit of RC=5 ns. Photographs taken at short gaps ($\sim$1 mm) confirm the occurrence of space-charge type of spark breakdown through streamer formation by the superposed effect of a large number of electron avalanches created by an α-particle At large gaps ($\sim$5 to 30 mm), no spark breakdown occurs and only the primary electron pulses are observed. This is understood in the light of the highly non-uniform electric field and the corona zone near the wire in the spark counter geometry Some finer details of the pulse-forms at large gaps and the possible effect of negative ion formation are also discussed.

INTRODUCTION

Many phenomenological properties of the spark counter have been studied (Connor, 1952, Savel, 1952, Saha and Nath, 1957, Kawata, 1961) and a number of practical applications (Fleury, 1959, Gupta and Saha, 1961, Gupta and Saha, 1962) of these made Not much work has, however, been done so far to understand the basic mechanism of the spark breakdown in the counter. The spark breakdown processes in gases under overvolted parallel plate gaps have been extensively studied by Raether (1961), Loeb (1956), Meek (1953), Penning (1957) and others (Pfaue and Raether, 1959). The processes in the spark counter are, however, complicated by the strongly non-homogeneous electric field in the wire-to-plate geometry and the existence of the densely charged corona zone near the

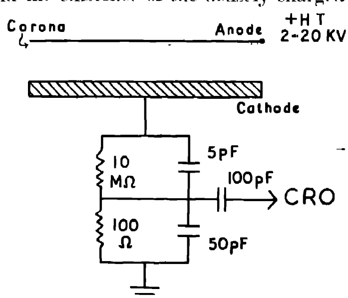


Fig. 1. Schematic diagram of spark counter and the differentiating pulse divider.

wire (Fig 1). It is, therefore, important to study the specific problems in the spark counter in the light of our existing knowledge in the homogeneous field.

An organic vapour or gas between two parallel plates under a steady potential shows two distinct types of electrical breakdown processes (1) the Townsend regenerative gas discharge (γ-process) and (2) the space-charge breakdown by streamer formation (Fig 2). The former is caused by generally strong cathodic

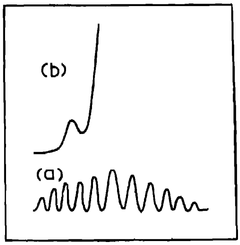


Fig. 2 (*a*) Typical forms of Townsend regenerative discharge pulses, (*b*) Space-charge breakdown pulses.

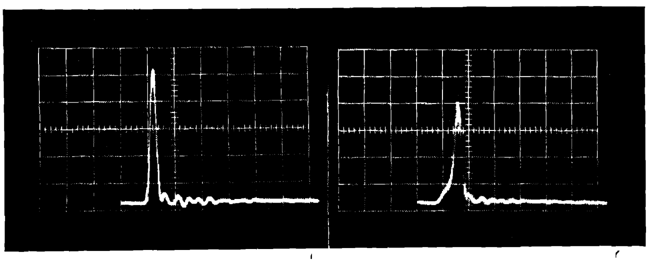
secondary electron emission in gases with large γ_{photon} satisfying $\gamma(e^{\alpha d}-1)=1$, even though single primary electron avalanche $e^{\alpha d}$(α — the Townsend first coefficient, d — gap length) lies well below 10^8 electrons. In gases with smaller electron emission, a series of secondary electron avalanches may eventually produce large space-charge accumulation and lead to space-charge breakdown In the second process (2), a single electron avalanche must carry $\geqslant 10^8$ electrons and positive ions, generating strong space-charge field (near the anode), which in turn sets up conducting electron streamers extending across the entire gap (Loeb *et al*, 1948, Loeb, 1955, Raether, 1959) and causes spark breakdown This would take place readily in gases with poor γ_{photon} under sufficiently overvolted gap and much earlier than the process (1) could occur.

We describe below results of our preliminary study of the structure of the electrical potential pulses produced at the spark counter cathode by α-particles in atmospheric air using a fast quenching circuit (RC$\sim$5 ns) as shown in Fig 1, and photographed on a Tektronix 531A oscilloscope Nine different gap lengths between 0.5 mm and 30 mm were used The results strongly suggest a space-charge type of breakdown taking place at short distances under the strong non-homogeneous electric field existing. It seems that although the single electron avalanches in the small gaps used do not exceed 10^4-10^5 electrons, super position of the avalanches in time and space due to about 10^4 to 10^5 electrons released by an α-particle within a few nanoseconds enlarges the avalanche due to each α-particle to $\geqslant 10^8$ electrons. The condition for space charge breakdown by streamer formation is thus set up. This view is supported by a recent work of Schlumbohm (1962) on the α-particle spark breakdown of gases in a homogeneous electric field (published while this manuscript was under preparation). Only a qualitative interpretation of the mechanism is attempted by us for the present in view of the complications introduced by the non-homogeneous electric field and the corona phenomenon. More measurements with better defined conditions would be required for a quantitative understanding.

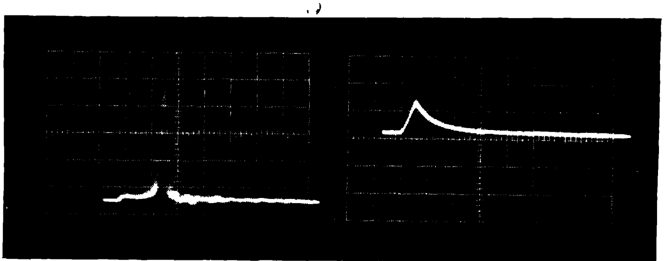
THE OSCILLOGRAMS AND THEIR EXPLANATION

In our previous works on spark counter, only small wire to plate gap (~1.5 mm) was used. Here for large spark gap (upto 3 cm) an additional provision had to be made for applying steady D.C. potential up to 20 KV with fine adjustments. Atmospheric air at about 35°C and 40 per cent R. H. was used. The spark gaps 'd' chosen were, 0.5, 1.0, 1.2, 5.0, 10.0, 15.0, 20.0, 25.0 and 30.0 mm. The potentials across the gaps were adjusted respectively to 2.0, 2.6, 3.0, 4.4, 7.5, 9.6, 12.5, 16.0 and 20 KV. such that they were approximately 200 V above the threshold of the sparking with α-particles in each case. Without the α-particles, the counter showed zero background over long hours.

The photographs of the potential pulses across the series quenching resistor (R~100Ω), were taken at each of the gap lengths. These are reproduced in Figs. 3 and 4.



Traces 3(a) & 3(b)



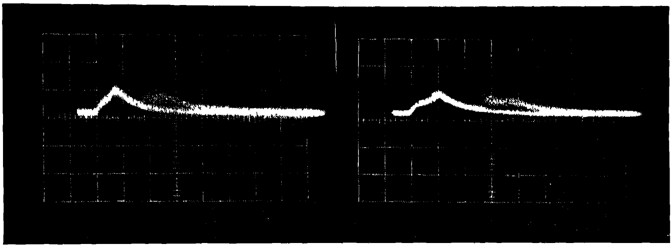
Traces 3(c) & 3(d)

Traces a, b and c are at gap lengths 'd' = 0.5, 1.0 and 1.2 mm respectively, using oscilloscope sweep speed = 0.1 μ sec/cm and vertical sensitivity = 10 V/cm.
Trace d is at 5 mm gap length using sweep speed 0.1 μ sec/cm and vertical sensitivity = 0.5 V/cm.

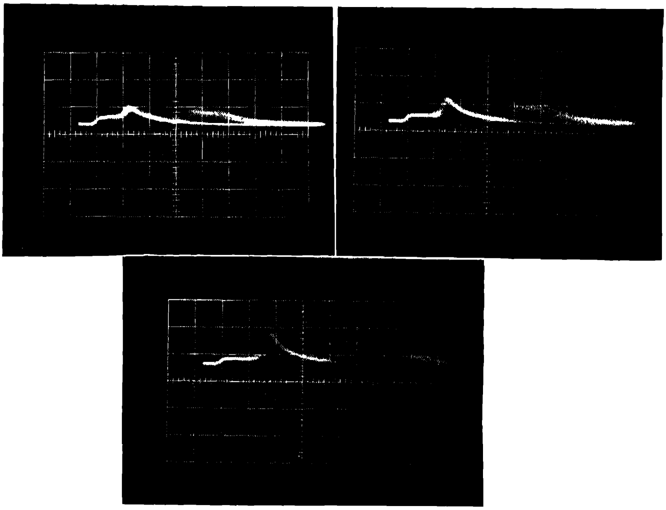
As explained under discussion to follow, we suggest the following interpretation for the observed pulses :

1. In Fig. 3, photographs *a* to *c*, the space-charge type of spark breakdown is occurring with streamer formation preceded by a critically large primary avalanche ($e^{ad} \geqslant 10^8$) electrons) produced by a single α-particle

2. At the smallest gap $d = 0.5$ mm, trace (a), the primary electron pulse is not resolved over the oscilloscope as it is almost instantaneously overtaken by



Traces 4(e) & 4(f)



Traces 4(g), 4(h) & 4(k)

4. Traces e, f, g, h and k are at gap lengths 'd' = 10. 15, 20, 25 and 30 mm. using sweep speed 0.1 μ sec/cm and vertical sensitivity = 0.5 V/cm.

the strong streamer breakdown pulse. At the gap $d = 1.2$ mm, trace *c*, the primary electron pulse is clearly resolved first and this is followed by a streamer breakdown pulse after a time delay of about 100 ns. The trace (b) indicates the transition between (a) and (c).

3 At $d = 5$ mm, the trace obtained (d) shows clearly (on a larger vertical sensitivity of the oscilloscope) the primary electron component of the pulse, but there is no trace of any spark breakdown up to about 700 ns. In fact, it never occurs even when observed on a much longer sweep speed

4 In Fig. 4, traces *e* to *k*, a close examination of the traces shows a small electron component of the pulse preceding the main electron component. The latter gradually develops in amplitude and resolves itself more and more from the smaller pulse with increasing gap length. The smaller pulse component seems to arise from the primary electron avalanches within the corona region which has extended considerably at higher gap lengths.

There is again no spark breakdown occurring in these cases.

5. In traces *e* to *k* we find alongside the main electron component pulse a gradually developing hazy and ill-focused broad pulse occurring at an increasing time delay from the main electron peak. Its amplitude has been found to be strongly sensitive to overvotage of the gap. We suggest that the broad pulse is due to the secondary avalanches produced by electrons released from the negative ions of oxygen (O_2^-) formed by electron capture.

DISCUSSION

(i) *Estimation of electron avalanche size*

The carrier number $n_e \sim e^{\alpha d}$ in the primary electron avalanche should now be estimated in order to justify our proposed explanation of the space-charge breakdown pulses Values of α/p over a wide range of E/p values in some gases (Schlumbohm, 1959) are known, but they are hardly useful in our calculations because of the strong non-uniformity of the electric field and the presence of the corona region. We know, however, that in a pulse circuit where the potential developed across the external resistance ($\sim 100\Omega$) does not extend beyond a few times T_- (the electron transit time from the cathode to the anode), the time rise $\dot{U}$ of the electron potential pulse $U(t)$ at any instant t is a measure of n_e through the relation

$$n_e = \frac{Cd^* \dot{U},}{ev_-} \quad \ldots \quad (1)$$

$$= 0.7 \times 10^{10} \dot{U} d^*,$$

taking $C = 50pF$, $v_- = 5 \times 10^7$ cm/sec and $\dot{U}$ in Volt/ns, where C is the total capacity of the discharge space, v_- the electron drift velocity, e the electronic charge and d^* the remaining gap length outside corona.

The values of n_e estimated by taking $\dot{U}$ from our oscilloscopic traces for $d =$ 0.5, 1.2 and 5.0 mm are shown in Table I, taking d for d^* approximately. The accuracy of the n_e values calculated is limited by the rise time of the oscilloscope (~20 ns/cm), as well as by the fact that we have used same v_- for all the gaps, which may not be strictly correct. Even allowing for ~20 per cent uncertainty in the calculated values, their striking regularity with the gap length is remarkable.

TABLE I

$d \rightarrow$	0.5 mm	1.2 mm	5.0 mm
$\dot{U}_{obs}$	50 V/10 ns	3 V/20 ns	0.5 V/50 ns
$n_{e\,calc.}$	1.7×10^{9}	1.2×10^{8}	$\sim3\times10^{7}$

The avalanche magnitude comes out to be just critical (~10^8) for streamer formation* at $d = 1.2$ mm. At $d = 0.5$ mm, n_e very much exceeds the critical value, and that is why the very fast spark breakdown pulse occurring here overlaps the primary electron pulse. Finally, at $d = 5.0$ mm, n_e falls below the critical value, and no streamer breakdown occurs here at all. The reason why the n_e value should fall below the critical value above a certain 'd' must lie clearly in the electric field strength $E_r{}^*$ prevailing at a distance r^*, i.e. just outside the corona region, at large gaps and the effective distance within d^* over which the gas amplification takes place (see section iii of discussion).

(ii) The streamer delay time

The time duration required for a visible potential rise to occur due to the streamer formation can be measured by the time delay T_d of the point C from the near saturation point B of the primary electron pulse (Fig. 5) on the oscillo-

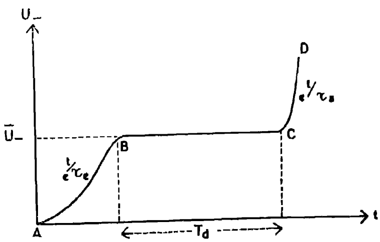


Fig. 5. Typical pulse potential variation with time defining the pulse characteristics. AB=rising primary electron pulse, BC=plateau region, CD=rapidly rising space-charge breakdown pulse.

*Raether (1959) has recently shown that the probability of streamer formation passes through a maximum, when $n_e \geqslant 10^9$. Here the increase in the electron number $dn_e/dx > e^{\alpha x}$, i.e. there is an over exponential growth.

scope trace. This is an important characteristic in all the streamer phenomena. The time constants τ_c and τ_s are the other two pulse characteristics defining the rise time of the primary electron pulse and the spark breakdown pulse respectively. In general τ_s would be only a few nanoseconds and much shorter than τ_c, on account of the rapidly rising streamer at C. The delay time T_d depends strongly on the saturation (plateau) potential (Schlumbohm, 1962) of the electron pulse $\bar{U}_-$. As $\bar{U}_-$ reaches the value corresponding to the primary avalanche magnitude $e^{\alpha d} \geqslant 10^8$, a certain minimum positive ion density n_+ is attained and the space-charge field is strong enough to generate secondary electron avalanches due to gaseous photoelectrons (near the anode) These are at first too small to give any observable potential rise, but as time goes on, more and more space charges accumulate, till the time T_d has elapsed, when the streamer potential starts rising visibly above the plateau. Since T_d is governed by the exact moment of sufficient space-charge accumulation, it may have a large statistical fluctuation (Franke, 1960). Besides this, T'_d has been found to depend on the formation of negative ions in certain gases (Schlumbohm, 1962) and the state of the overvoltage (Schlumbohm, 1962) across the gap.

In our photographs, a systematic increase in the delay time from zero to a few nanosecond at 1 mm and then to $\sim$100 ns at 1.2 mm gap is note-worthy. This may arise due to a combination of various causes mentioned above Many more photographs of the pulses at each gap length may have to be taken before assigning a definite reason to the delays, although a strong correlation of T_d with the gap length suggests itself, perhaps due to the gradually weakening field outside the corona region from 0.5 to 1.2 mm gap length.

(iii) *Influence of corona on the electric field distribution*

We have so far disregarded any possible influence of the corona formation on the spark counter action In reality, the corona seems to play an important role and is something peculiar to the spark counter geometry where a very strong electric field normally exists at the anode wire surface and the field falls off rapidly outside

In the atmospheric dry air the corona sets in at an electric field strength $\geqslant$ 30 KV/cm. A part of it generally contains feebly ionised invisible air molecules, and a visual corona of almost fully ionised gas sets in at a higher field strength $\geqslant$ 50 KV/cm nearer to the wire. The corona produces a strongly stabilising effect on the electrostatic stress between electrodes by increasing the wire-radius virtually to r^*, the extension of the visual corona, because the field outside the corona is substantially lower than the original field strength at the wire surface itself, and the chance of any electrical breakdown is therefore reduced.

In the cylindrical wire-to-plate system the field strength at a distance x from the axis of the wire of radius r at a potential V_r is given by

$$E_x = \frac{2d_0 V_r}{x(2d_0-x)\, ln\,(2d_0-r)/r}\,, \tag{2}$$

where d_0 = distance of the cathode (at zero potential) from the wire axis. The field strength E_r or $E_r{}^*$ is maximum at the wire surface and is obtained by substituting $x = r$ or r^* in (2), according as we take the real or the virtual radius.

To calculate roughly the possible gas multiplication by electrons outside the corona, we have evaluated the electric field strength from (2) for two gap lengths $d_0 = 5$ mm and 20 mm at various values of x. A visual corona extension of $\sim$2 wire diameters ($r^* \sim 0.2$ mm) is assumed for $d_0 = 5$ mm and $\sim$5 wire diameters ($r^* \sim 0.5$ mm) for $d_0 = 20$ mm (from rough eye estimation).

The results of calculation are shown in Fig. 6. It will be seen that for $d_0 = 5$ mm, the electric field strength falls below 20 KV/cm at $x > 0.5$ mm, and

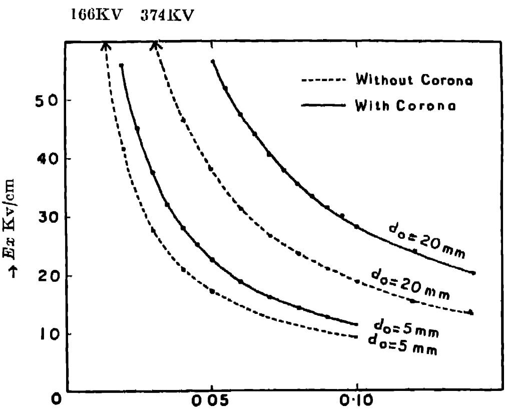


Fig. 6. Electric field strength for two gaplengths $d_0 = 5$ and 20 mm. Full line denotes the calculated field strength corrected for corona and the dotted line denotes the uncorrected field strength.

for $d_0 = 20$ mm, the field falls below 25 KV/cm at $x > 1$ mm, so that beyond these limits of x, the field-strengths are not generally sufficient for gas multiplication and may be left out of account.

The Townsend first coefficient $\alpha(x)$ varies strongly with E_x and can be roughly taken from Schlumbohm's (1959) data. By a graphical plot of α (x) against x

over the effective field region, the average value of αd and the corresponding gas multiplication factor $e^{\alpha d}$ are calculated and shown in Table II. Assuming that an α-particle releases on an average about 1000 electrons in the effective field region the total gas multiplication will be about 10^5 and $10^{6.5}$ in the two cases respectively. These are considerably below the critical value of 10^8 required for streamer formation. The absence of spark breakdown at large gap lengths is thus qualitatively understood.

TABLE II

d_0	corona extension (r^*)	E_r^* KV/cm	Averaged (αd)	$e^{(\alpha d)_{av.}}$
5 mm	0 2 mm	56 3	3 6	10^2
20 mm	0.5 mm	57.0	8.2	$10^{3.5}$

It is clear from the above two typical cases of field calculation that the increasing extension of corona has a greater stabilising effect on the electrical field outside it, in that the field distribution in the gap tends more towards homogeneity. As a result, the value of αd over the effective field region increases with gap length, giving higher gas multiplication $e^{\alpha d}$.

There is yet another important consequence of the corona phenomenon which is prominent at large gaps The normal corona region is almost field free on account of strong positive ion density existing over this region. As an α-particle enters the corona region, it releases a large number of electrons very close to the wire which momentarily destroy the normal corona effect and build up a strong field close to the wire. This may exist for a very short time during which the electrons are all collected at the wire and the corona is reestablished. There is, therefore, a weak corona electron pulse of fast rise time having a long plateau, from which eventually will start the main primary electron pulse from outside the corona. The latter may be delayed considerably (upto $\sim$100 ns), because during the transition period of the restoration of corona, the field strength at the corresponding points would be much weaker than what would have been with the corona fully established (Fig. 6). The plateau length will depend on the extension of the corona region which increases with the increasing gap length (traces *c* to *k*).

This is, therefore, another form of the space-charge effect induced by the α-particle within the corona. It shows itself by a two-step appearance of the primary electron pulse, as is clearly seen in our traces from *e* to *k* in Fig. 4.

In small gaps up to $d = 1.2$ mm, the corona extension is very little and the average electric field strength extending up to the cathode outside the corona is stronger than at higher gap lengths. The corona electron collection is therefore much weaker and faster (may not be observable at all), whereas the main electron component will be much stronger, and may merge into the corona pulse, as appears to be the case in Fig 3 (traces *a* to *d*).

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